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Mars Sample Return – An Overview of the Capture, Containment and Return System

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Abstract

The Mars Sample Return campaign aims at bringing back rock and atmospheric samples from Mars to Earth to answer key questions about Mars' biological evolution by means of four elements. The first one, Mars 2020, landed on the Red Planet on February 18, 2021 and has to date collected a number of samples through the Perseverance rover. The two subsequent missions aim to recover the sample tubes, launch them into Mars orbit and transport them back to Earth. The last element is the Sample Receiving Facility, where the samples would be analyzed. These elements are currently in the planning and design stages of development and represent an international effort comprising NASA, the European Space Agency and many industry partners. The work presented here provides an overview of the current design and concept of operations of the NASA-provided Capture, Containment, and Return System (CCRS), which is the payload of the ESA-provided Earth Return Orbiter (ERO). ERO would rendezvous with the orbiting samples and CCRS would capture them, contain them and robotically insert them into a capsule that would return the samples to Earth, the Earth Entry System (EES). About three days before arrival on Earth, CCRS releases the EES on an Earth entry trajectory, which then passively enters Earth's atmosphere, descends on a highly predictable trajectory and safely lands notionally at the Utah Test and Training Range. The decision to implement Mars Sample Return will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.
Keywords: Mars Sample Return, Planetary Protection, Break the Chain, Containment Assurance.

1. Introduction

The Mars Sample Return (MSR) campaign aims to seek signs of ancient life on the Red Planet by collecting compelling samples of rock, regolith (broken rock and dust) and atmosphere for a possible return to Earth [1, 2, 3, 4]. Years of data from past missions to Mars have confirmed that some areas offered habitable conditions that were capable of supporting life in the past. Much of this warmer, wetter period is believed to have occurred about three billion years ago, in the same geologic timeframe as early life was blooming on Earth. This commonality raises the prospect that discoveries on Mars can give important insights about the origin and evolution of life on Earth.

MSR would fulfill many years of external guidance to NASA, including the top recommendation of the U.S. planetary community in their most recent national strategy, titled Vision and Voyages for Planetary Science in the Decade 2013-2022 [5]. Beyond the search for life, the MSR campaign could also help scientists understand the detailed geological history of Mars, the evolution of its climate, and any hazards in the dust of the Red Planet that could affect future human explorers.

Figure 1 shows the four elements of the MSR campaign. The first one, Mars 2020, launched on July 30, 2020 and landed in the Jezero Crater on February 18, 2021. To date, it has collected 1 atmospheric and 12 rock samples through the Perseverance rover. The second element is the Sample Retrieval Lander (SRL), which would launch no earlier than 2028 to carry the Sample Recovery Helicopters (SHRs) and the Mars Launch System (MLS). While Perseverance would be the primary means to deliver the samples, the SHRs would play a back-up role in case Perseverance would become unable to perform this task. The samples would thus be positioned inside a container aboard the MLS, which would perform the first launch from another planet to put the samples in Mars or-

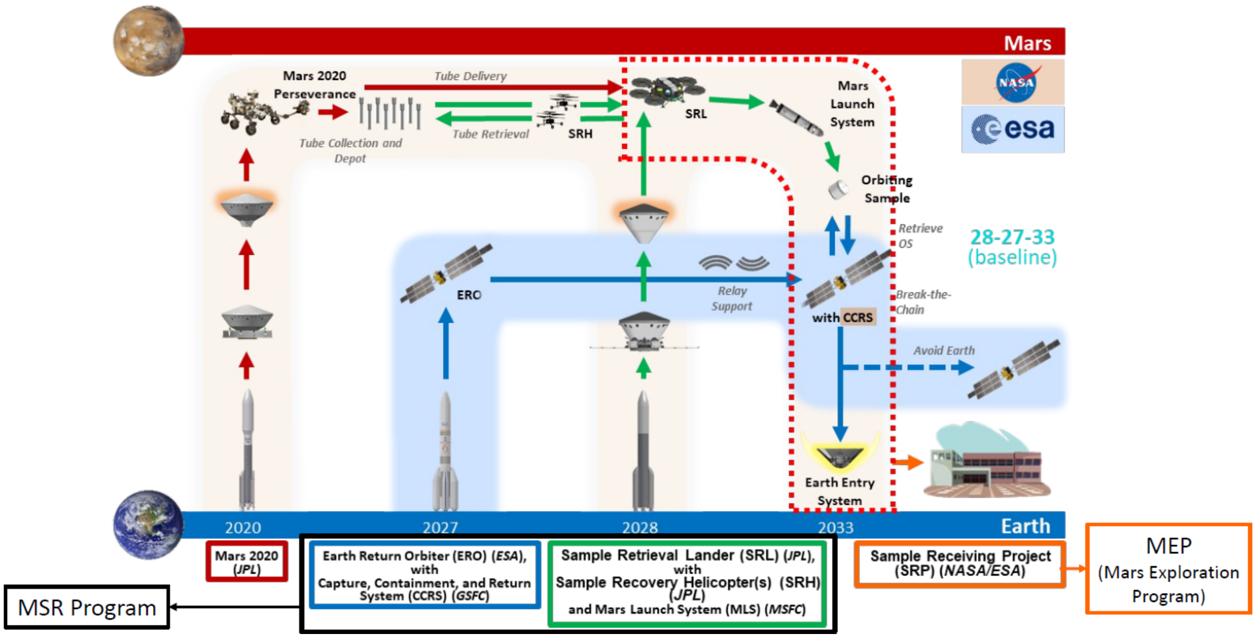

Fig. 1: Elements of the planned MSR campaign.

bit. The third element, the Earth Return Orbiter (ERO), would launch no earlier than 2027 to relay support for SRL, capture the orbiting sample (OS) and return it safely to Earth. These two elements, which form the MSR Program, are currently in the planning and design stages of development and represent an international effort comprising NASA, the European Space Agency (ESA) and many industrial partners. The fourth element of the campaign is the Sample Receiving Project (SRP), which is part of the Mars Exploration Program and aims to design and build a facility that would host and analyze the returned samples under the most protective measures, comparable to biohazard safety level 4, generally employed for safely handling biological toxins and known infectious agents used in Earth-based research labs. The samples would be kept under these stringent containment conditions and not released to other laboratories until it is determined that they are safe through extensive analyses or rendered biologically inert through sterilization. Similar to the lunar samples from the Apollo missions to the Moon, the samples to be returned from Mars would be studied in great detail for many decades by future generations of scientists, using instruments and techniques that have yet to be invented.

The focus of this work is the Capture, Containment and Return System (CCRS), which is the NASA-provided payload of ESA's ERO. The role of CCRS is to capture the OS upon rendezvous with ERO, contain it and robotically insert it into the Earth Entry System (EES), a capsule that would return the OS to Earth. About three days before arrival on Earth, CCRS would release the EES on an Earth entry trajectory. The EES would then passively enter Earth's atmosphere, descend on a highly predictable trajectory and safely land notionally at the Utah Test and Training Range. This work presents an overview of the current design and concept of operations of CCRS.

2. Motivation and background

Mars is a challenging environment for active biology or biomolecules due to the following factors: 1) the high-radiation environment caused by Mars' thin atmosphere damages biomolecules, 2) temperature and water activity on Mars rarely (if ever) reaches levels required for active metabolism, 3) absent active metabolism biomolecules will be degraded significantly. As a matter of fact, the samples being collected by the Perseverance rover are from the first few centimeters of a planetary surface that is very dry and highly irradiated naturally by the Sun, which would sterilize all known cellular biology directly exposed at the surface. This is one of the reasons why NASA's science strategy is focused on finding traces of ancient life from long ago, when the Martian environment was wetter and warmer, and not modern life in these harsh conditions.

In general, potential hazards present a very low likelihood. For example, host-pathogen relationships are evolutionary in nature and Mars-Earth exchange is infrequent, so any pathogens are likely to be non-specific to Earth species (including humans). Invasive species from Mars would also encounter a largely inhospitable environment on Earth. Finally, Mars material arrives naturally on Earth as meteorites, some on fast paths that do not expe-

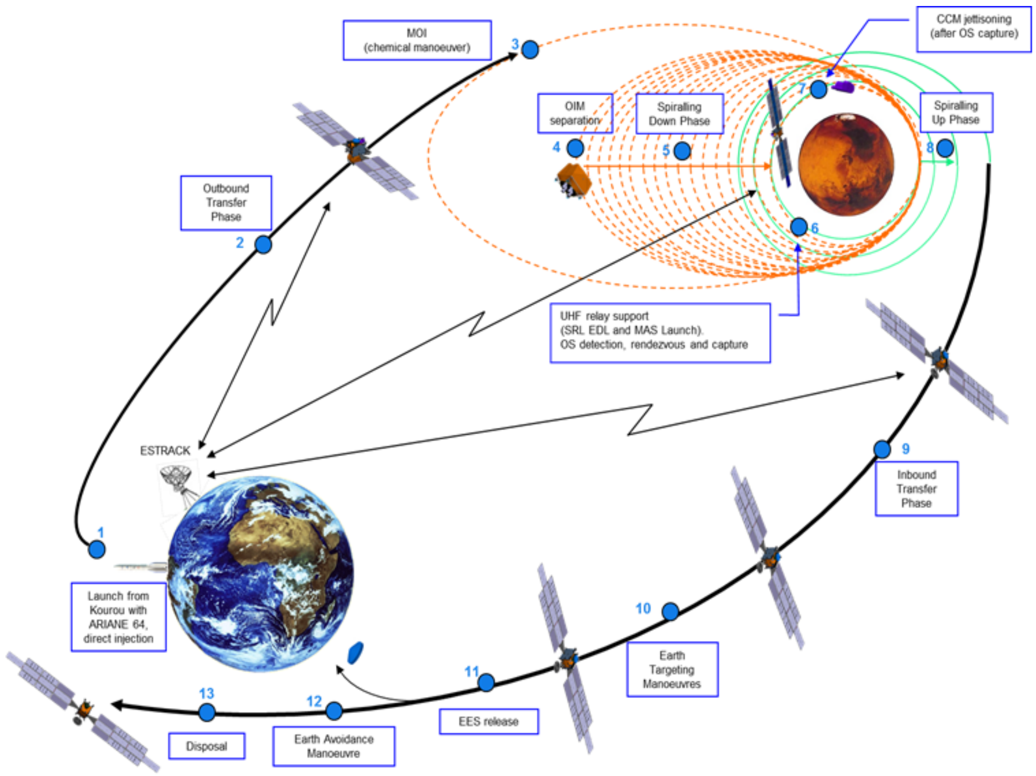

Fig. 2: Overview of the ERO mission with the main phases highlighted.

rience any sterilization. Despite a low hazard likelihood, nonetheless, the potential for a high consequence cannot be excluded. As a result, MSR plans to adopt a "Safety First" approach by safely containing all unsterilized Mars material returned to Earth.

This approach is in line with current policies [6, 7, 8], which all affirm the need for protecting solar system bodies from harmful contamination by terrestrial materials (forward planetary protection – FPP) while protecting the Earth-Moon system from possible harmful extraterrestrial contamination that may be returned from other solar system bodies (backward planetary protection – BPP).

For restricted sample return missions (i.e., those whose samples could cause harmful biological contamination of the Earth's biosphere), the translation of these policies into engineered systems consists of establishing and implementing a strategy and design concepts to *break the chain* of contact with the target body, isolate, and robustly contain the restricted samples. This is in practice the role CCRS plays by sterilizing the contaminated surfaces, enforcing a clean zone and containing the sample tubes in two redundant containers. ERO further contributes to this by avoiding Earth after release of the EES.

3. Mission and payload overview

Figure 2 shows an overview of the ERO mission. ERO would launch from Kourou, French Guyana, on an Ariane 64 on a direct injection to Mars. Near-Earth commissioning would continue for about 30 days, while the outbound transfer with heliocentric parking orbit about 3 years. Mars orbit insertion would occur through chemical maneuver for about 2 weeks, before starting spiralling down for less than 1 year. In low Mars orbit, over the course of 1-1.5 years, the following activities would take place: ultra-high frequency relay support for the entry, descent and landing of the Sample Retrieval Lander and for the launch of the Mars Launch System; rendezvous with the orbiting sample and containment operations. With the orbiting sample secured in the CCRS payload, ERO would start spiraling up for less than 1 year and then head back to Earth through an inbound transfer of about 1 year. The EES delivery phase would occur approximately 3 days before arrival on Earth, with the EES being released and ERO performing an Earth avoidance maneuver that would park it in a heliocentric orbit that would avoid Earth for at least 100 years (i.e., as far as can be reasonably predicted).

Figure 3 provides an overview of the CCRS payload with its main elements and subcomponents: 1) the Capture Enclosure (CE), 2) the Assembly Enclosure (AE), 3) the Earth Entry System (EES), and 4) the Micrometeoroid

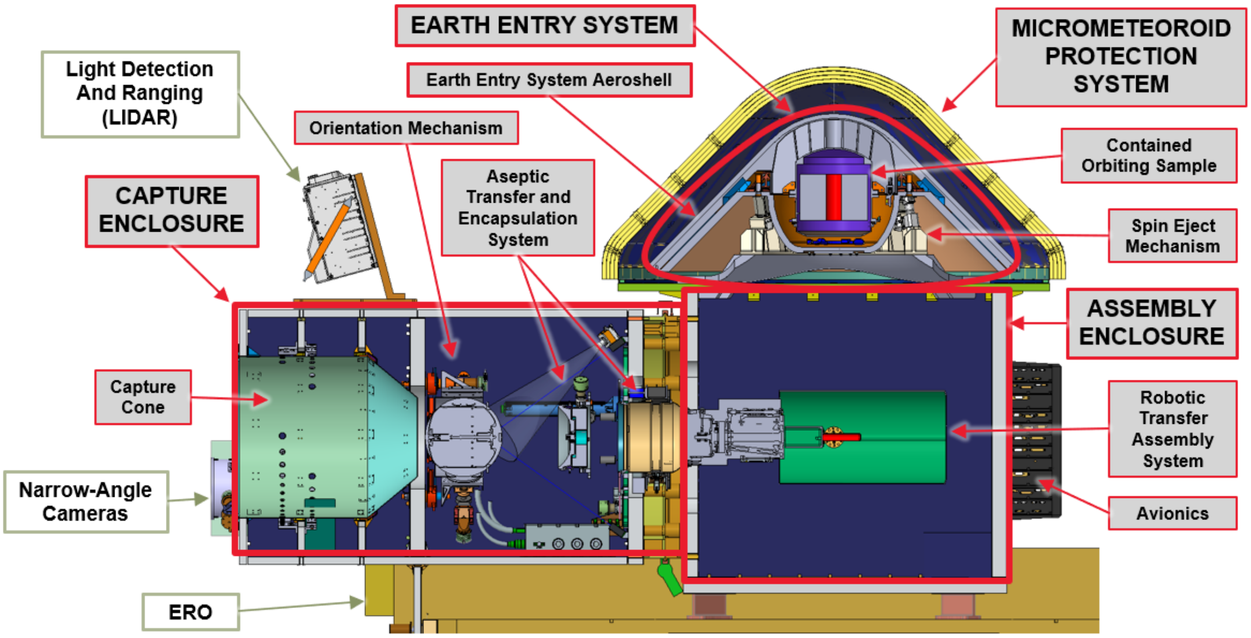

Fig. 3: Overview of the CCRS payload with its main elements highlighted.

Protection System (MMPS).

The Capture Enclosure, directly exposed to Mars material, would be the place for capturing and containing the OS while providing control of Mars particles, as well as a containment and sterilization capability that serves to break the chain of contact between Mars and Earth.

After capture, the OS would be sealed inside a Primary Containment Vessel (PCV) and the seamline of the PCV would be heat sterilized. The Assembly Enclosure, considered clean and not exposed to Mars material, would receive the OS in the sterilized PCV and robotically assemble it into a secondary containment vessel (SCV) inside the EES Aeroshell. The combined OS, PCV and SCV would form the Contained OS (COS).

During the spiral-up phase, where electric propulsion is used to raise ERO's orbit, the Capture Enclosure would be ejected in Mars or heliocentric orbit; options for final disposition of the CE are actively being evaluated with regards to both FPP (e.g., a stable orbit of required lifetime, or bioburden with or without burnup/breakup analyses) and BPP (Mars particle control).

The combined EES Aeroshell and COS would form the Earth Entry System (EES) and reside inside the Micrometeoroid Protection System (MMPS), a protective debris shield, during transit back to Earth; the MMPS would support achievement of BPP compliance by providing micrometeoroid protection measures to ensure integrity of the entry system.

Upon successful delivery by ERO to the desired release position, velocity and attitude, the EES would be released from CCRS through a spin eject mechanism on an Earth return path with high reliability and precision.

The EES would then deliver the Mars samples to the selected landing site on Earth, providing containment of the COS throughout approach, entry, descent and landing. BPP compliance within this phase would be addressed through trajectory selection, redundant containment layers, thermal protection for entry, and impact resistance.

The AE and MMPS would remain attached to ERO, which would be guided, under ESA's direction, to a stable heliocentric orbit that will not intersect Earth for at least 100 years in the nominal mission plan.

All these operations have been subdivided into specific phases, which will be described in more detail in Sec. 4.

4. Concept of operations

4.1. Capture and Configuration

In the Capture and Configuration phase, ERO performs a rendezvous maneuver with the OS using CE-mounted light detection and ranging (LIDAR) units and narrow-angle cameras to detect and track the OS. As the OS approaches CCRS, a linear transfer mechanism (LTM) and lid remains stowed and opened, respectively, until two planes of light-emitting diode (LED) sensors detect the OS within the capture volume. Once the capture sensors are triggered, the linear transfer mechanism autonomously deploys within the capture cone to physically capture the OS, while the lid simultaneously closes to contain Martian dust within the capture volume. The linear transfer mecha-

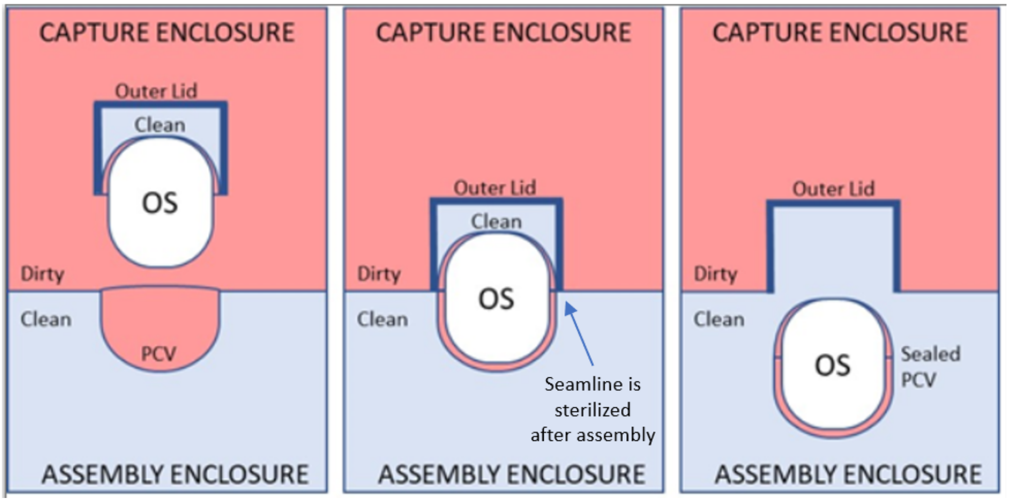

Fig. 4: Schematic view of aseptic transfer.

nism funnels the OS into the orientation mechanism (OM) on the other end of the cone. The orientation mechanism manipulates the OS into the correct orientation and a set of cameras capture images of the OS end-caps as a means of ground verification that OS configuration is successful.

4.2. OS Installation and Aseptic Transfer

In the OS Installation and Aseptic Transfer phase, operations are performed to install the OS into its Primary Containment Vessel (PCV) and then permit the PCV to exit the Capture Enclosure with no unsterilized Martian material outside the PCV.

The lid of the PCV is launched on the seating mechanism (SM), a component of the Aseptic Transfer and Encapsulation System (ATES). While the OS is securely held in the orientation mechanism, the seating mechanism translates the PCV lid toward the OS until it docks to an exposed interface on the OS. The assembled lid/OS is then extracted from the orientation mechanism, flipped 180° and maneuvered to a position above the PCV base.

To seal the PCV, a heated shrink fit operation is performed where the rim of the PCV base is locally heated to $> 500°$C, which expands the interface. While the base is heated, the ambient-temperature PCV lid (and OS) is driven into the base and the base is cooled to complete the seal. The heated shrink fit joint is robust enough to remain sealed during landing load tests. During this operation, an outer lid is also installed over top the PCV, which will close out the hole left once the PCV is extracted. This outer lid becomes the barrier that prevents any particles from migrating from the Mars dirty Capture Enclosure to the Earth clean Assembly Enclosure (see Fig. 4).

The newly formed PCV seal is then heated to $> 500°$C for 5 seconds so that any material on exposed portions of the PCV lid or base is sterilized. The sterilization time/temperature profile was selected to destroy any potential biohazards from Mars. The sterilization parameters are designed to ensure pyrolysis (i.e., destruction) of any potentially catalytic proteins, which MSR has identified as the most resilient form of possible biological contamination. These parameters are well in excess of those required to sterilize the bacterial endospores that are typically considered the bounding case for forward planetary protection.

The OS contained within the PCV is now ready to be released to the Robotic Transfer Assembly System (RTAS) for installation into the EES.

4.3. EES On-Orbit Assembly

In the EES On-Orbit Assembly phase, the combination of PCV, SCV Lid and Aerothermal Closeout, called PSA, is removed from the ATES separation mechanism and installed into the EES. There are several steps involved in the operation:

1. The PCV lid is released from the seating mechanism while still constrained by the ATES base separation mechanism.

2. RTAS moves the end effector (EE) into contact with the PSA, at which point the EE gripper partially closes to cage the PSA.

3. With the PSA caged, the ATES separation mechanism is activated to fully release the PSA.

4. RTAS retracts the PSA out of the ATES separation mechanism and, once in free space, the RTAS EE gripper fully closes to pull the PSA into rigid contact.

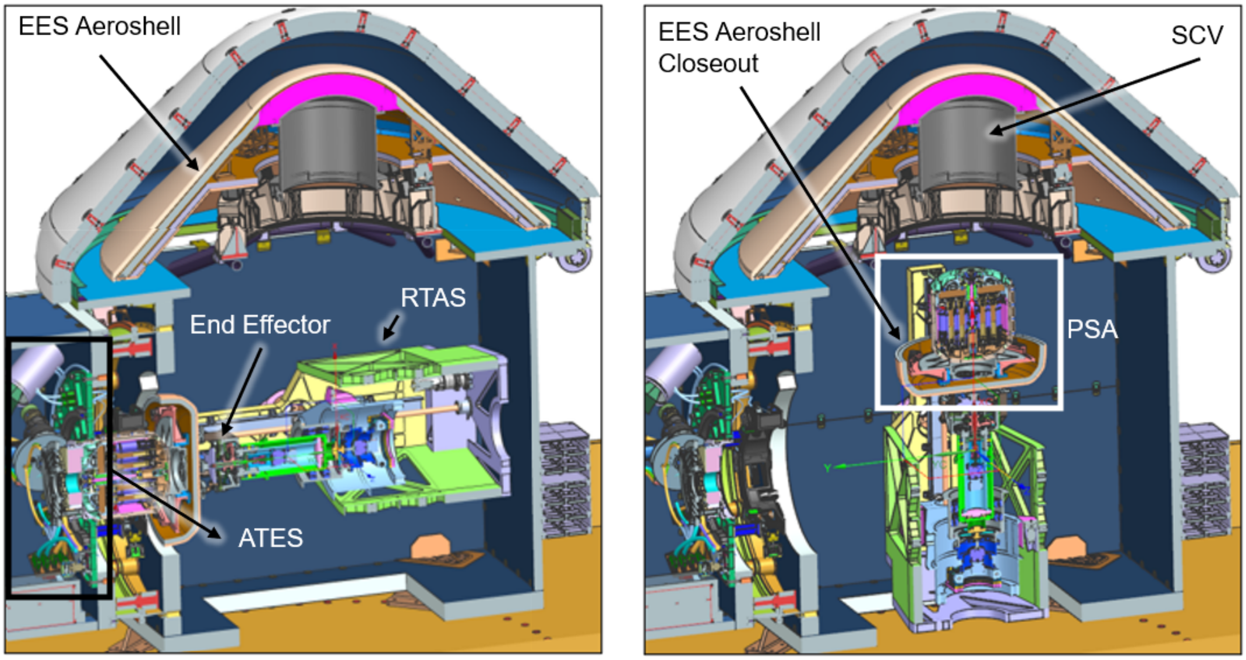

Fig. 5: Schematic view of the EES on-orbit assembly. The Robotic Transfer Assembly System rotates to extract the samples attached to the PSA from the Capture Enclosure and install them into the EES Aeroshell at the top of the Assembly Enclosure.

5. RTAS rotates 90° to align the PSA to the SCV body in the Earth Entry System;
6. RTAS inserts the PSA into the SCV body until axial contact is made.
7. While maintaining an axial load, the RTAS EE gripper partially opens to disengage from the PSA.
8. The RTAS EE torque mechanism then rotates the PSA to latch the PSA to the SCV body while forming a containment assurance seal and hot gas barrier seal.

These steps enable the orbiting sample to be redundantly contained and would represent the first on-orbit spacecraft assembly performed at Mars (Fig. 5).

4.4. Protection, Jettison and Release

The Protection, Jettison and Release (PJR) phase is the portion of the ERO mission timeline beginning at the completion of the on-orbit assembly of the EES and ending when the EES is released for entry into Earth's atmosphere. During the EPR phase, the assembled EES must remain protected from critical MicroMeteoroid and Orbital Debris (MMOD) damage during the flight from Mars orbit to Earth, and then must be released on the proper trajectory to ensure that it lands safely in the planned landing area at UTTR (see Sec. 4.5. for additional details).

The PJR phase operations plan can be viewed as being in three major stages:

- Jettison: the CE is ejected after completion of the EES assembly in order to reduce return mass and meet project BPP requirements.
- Mars-to-Earth transit: ERO transports CCRS toward Earth, while CCRS is mostly passive. The primary concern is protection of the EES from critical damage due to MMOD impacts.
- EES release: the EES is released toward Earth on the proper trajectory to land at the UTTR landing site.

4.5. Approach, Entry, Descent and Landing

In the Approach, Entry, Descent and Landing phase, the EES would passively travel toward Earth, without active guidance, for about 3 days before entering Earth's atmosphere. The EES entry and descent sequence from atmospheric interface to the ground lasts about 6 minutes, with a short period of high pressure and high heating environments generated by the EES' high initial velocity through the atmosphere. To survive this environment, the EES capsule would be protected by a Thermal Protection System (TPS) constructed of 3D Medium-density Carbon Phenolic (3MDCP) material.

Fig. 6: EES test article dropped at UTTR in early 2022 at speeds comparable to what would occur during an actual landing event.

The current EES design does not include a parachute to slow the EES descent for landing. This approach simplifies the design of the EES and eliminates a potential failure point while maintaining adequate safety margins. The cone-shaped EES capsule would be approximately 1.2 m to 1.4 m in diameter and would land with a terminal velocity of roughly 145 km/h. Simulations and ground-based testing have shown that this speed, combined with the soft soil anticipated in the landing area, would produce landing loads low enough to protect the Mars samples. The landing is expected to create a depression in the soil with a diameter about the same as the EES, with soil being ejected from the crater to a distance of approximately 15 m.

The EES landing is currently proposed to take place within the Utah Training and Testing Range (UTTR), the largest overland contiguous block of restricted airspace in the continental United States. Several landing sites in the continental US were considered and UTTR was selected because of its remote location featuring restricted access and special use airspace with a large landing area free from roads, structures, and hazardous terrain. The large, flat lakebed surface with minimal slope and soft playa soil properties are essential for softening the EES landing. Finally, UTTR possesses the infrastructure to track the EES during its entry, descent and landing that enables the recovery team to quickly locate and recover the vehicle and secure it for transportation to the sample receiving facility.

5. Compliance to planetary protection requirements

Planetary Protection (PP) requirements are specific to the type of mission and explored planetary body. Therefore, a mission is assigned one of five PP Categories (Categories I-V) according to the type of encounter it will have (e.g., flyby, orbiter or lander) and the nature of its destination (e.g., a planet, moon, comet or asteroid). If the target body has the potential to provide clues about life or prebiotic chemical evolution, a spacecraft going there must meet a higher level of cleanliness and some operating restrictions will be imposed [8].

Based on this, for FPP purposes, CCRS, as a NASA-provided hardware element launched with ERO, which is an ESA-provided Mars orbiter, is proposed as a Category (Cat.) III payload. This applies to spacecraft which, by the contamination they might cause, could compromise future investigations on a celestial body of significant interest relative to the process of chemical evolution and the origin of life. For BPP purposes, CCRS is managed under BPP constraints for Cat. V Restricted Earth Return, or Cat. V(r), missions, which applies to payloads directly involved in returning samples from a body with the potential to harbor life.

Note that CCRS will comply with NASA FPP requirements at delivery to ESA for integration and perform to NASA BPP standards as an element of the MSR Program during flight. The ERO spacecraft will comply with ESA's PP policies for Cat. III FPP and Cat. V(r) BPP mission through impact avoidance.

5.1. *Forward Planetary Protection*

To achieve FPP compliance for ERO (and the CCRS payload), the ESA strategy is to plan ERO orbits to be stable for longer than the required impact avoidance period or be limited in duration such that the probability of spacecraft failure during execution remains below impact probability requirements (i.e., $< 1\%$ impact probability for the first 20 years after launch, $< 5\%$ impact probability for the 30 years thereafter) consistent with COSPAR PP guidelines [7].

While Cat. III FPP compliance through Mars impact avoidance imposes no bioburden limits, ERO requirements include compatibility with bioburden assessments to ensure a bioburden-based compliance path is possible if mission success considerations result in Mars orbital parameters that exceed allowable Cat. III impact probabilities. Consistent with this strategy, CCRS will be compliant

to CCRS-ERO interface requirements mandating compatibility with bioburden assessments. The final disposition of CCRS hardware not returned to Earth is expected to rely on trajectories, in either Mars or heliocentric orbit, that satisfy both Cat. III requirements for FPP and Cat. V(r) requirements for BPP.

5.2. Backward Planetary Protection

The different elements of CCRS would comply with BPP requirements in different ways.

The CE, which is an element of CCRS that would be in contact with unsterilized Mars particles, would be ejected in space in either a Mars or heliocentric orbit. Disposal in Mars orbit would need to be compliant to Cat. III requirements for impact avoidance; in the event the orbital lifetime requirements cannot be met, the CE would be comply with bioburden limits for Mars missions. Disposal in heliocentric orbit would be compliant to both Cat. III FPP requirements and Cat. V(r) BPP requirements for Earth avoidance.

The EES would comply with Cat. III FPP and Cat. V(r) BPP requirements through sterilization and containment capabilities to break the chain of contact, anomaly detection, micrometeoroid protection, and robust and redundant containment through entry, descent and landing. Events such as initiation of Earth return, the Earth targeting maneuver and the release of the EES, may be subject to approvals from federal and international authorities. Should the aggregate flight system status or performance not meet desired levels, the EES is planned to remain with the ERO in a heliocentric orbit and options for later return would be assessed.

Finally, because there is a non-zero probability that Mars particles remain on the external surfaces of the AE, MMPS and spin eject mechanism (all on ERO), BPP compliance would be achieved by placing ERO on an Earth-intersecting trajectory up to 6 days prior to EES release and maneuver away from Earth 1-3 days prior to reaching the entry interface. This timeline may be adjusted to optimize delivery parameters for BPP and mission success. The CCRS hardware and ERO are expected, according to ESA requirements, to be disposed in a heliocentric orbit that avoids Earth for at least 100 years; Earth avoidance is addressed by NASA only through the CCRS-ERO interface requirements compliant to ERO BPP requirements.

6. Conclusion

The Mars Sample Return Program is being planned and designed to execute the first restricted Earth return mission from another planet since the early Apollo lunar landings, in order to bring back compelling samples that would shed much light on the history of the Red Planet, the Earth and the solar system. Despite the very low likelihood that the samples being collected by Perseverance may contain hazards that could potentially contaminate Earth's biosphere, a "Safety First" approach is being taken. This approach primarily consists of a series of on-orbit operations, such as sterilization, redundant containment and particle control, to break the chain of contact between Mars and Earth. CCRS would be the payload performing these operations onboard ERO. Once the samples are released on an Earth entry trajectory, ERO would execute an Earth avoidance maneuver and park itself in a heliocentric orbit.

It is worth noting that the decision to implement Mars Sample Return will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. As part of it, NASA, in cooperation with the U.S. Air Force and U.S. Army, is preparing a Programmatic Environmental Impact Statement (PEIS), which will analyze the environmental impact of the overall MSR program and ensure reasonable alternatives to the proposed action have been considered. This document is being made available for information purposes only.

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